

## A LABORATORY INVESTIGATION OF SUPERSONIC CLUMPY FLOWS: EXPERIMENTAL DESIGN AND THEORETICAL ANALYSIS

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## ABSTRACT

We present a design for high energy density laboratory experiments studying the interaction of hypersonic shocks with a large number of inhomogeneities. These “clumpy” flows are relevant to a wide variety of astrophysical environments including the evolution of molecular clouds, outflows from young stars, Planetary Nebulae and Active Galactic Nuclei. The experiment consists of a strong shock (driven by a pulsed power machine or a high intensity laser) impinging on a region of randomly placed plastic rods. We discuss the goals of the specific design and how they are met by specific choices of target components. An adaptive mesh refinement hydrodynamic code is used to analyze the design and establish a predictive baseline for the experiments. The simulations confirm the effectiveness of the design in terms of articulating the differences between shocks propagating through smooth and clumpy environments. In particular, we find significant differences between the shock propagation speeds in a clumpy medium compared to a smooth one with the same average density. The simulation results are of general interest for foams in both inertial confinement fusion and laboratory astrophysics studies. Our results highlight the danger of using average properties of inhomogeneous astrophysical environments when comparing timescales for critical processes such as shock crossing and gravitational collapse times.

*Subject headings:* hydrodynamics — shock waves — turbulence — ISM: clouds

## 1. INTRODUCTION

Advances in high-resolution imaging have revealed many astrophysical environments to consist of highly inhomogeneous media. Those images show that material on circumstellar, interstellar, and galactic scales are not smooth plasma systems but are often arranged into a large number of cloudlets or clumps immersed in a background of interclump gas. The presence of such “clumpy” mass distributions may have significant consequences for large-scale flows. These flows can dominate astrophysical processes. Examples include: mass loss from both young and evolved stars, strong shocks propagating through interstellar clouds, and mass outflows from active galactic nuclei (AGN). In each of these cases, a high velocity flow impinges on an ambient medium that is accelerated, compressed, and heated. The momentum and energy exchange between the driver (the winds or interstellar shocks) and the ambient medium can be an important source of luminosity, non-thermal particles, mixing of enriched elements and turbulence. Thus, the clumpy flows revealed in new images point to the need for increased understanding of how inhomogeneous media can change fundamental astrophysical processes and affect the evolution of different astronomical environments.

Understanding clumpy flow dynamics poses significant scientific challenges. The vast majority of theoretical treatments of astrophysical fluid flows have only considered smooth distributions of gas. A number of pioneering studies by Dyson, Hartquist and collaborators have attempted to understand the role of embedded inhomogeneities via (primarily) analytical methods (e.g., see (Hartquist *et al.* 1986; Hartquist & Dyson 1988)). One critical feature of these pioneering works was

treatment of clumps as unresolved sources of mass. This “mass loading” of flows via hydrodynamic and diffusive ablation was shown to produce important global changes in the flow pattern such as the transition of the flow into a transonic regime irrespective of the initial conditions. In general, it was shown that interactions of a flow with inhomogeneities might cause significant changes in the physical, dynamical, and even chemical state of the system.

Attempts to produce fully resolved numerical studies of clumpy flow dynamics have been hampered by speed and memory requirements of computers. In general, detailed studies have focused on interactions of a *single clump* with a global flow (Klein, McKee, & Colella 1994) (hereafter KMC), (Jun & Jones 1999; Lim & Raga 1999; Mac Low *et al.* 1994). The advent of adaptive mesh refinement (AMR) computational technologies has allowed resolved multiple clump systems to begin to be studied. In (Poludnenko, Frank, & Blackman 2002) (hereafter PFB) a numerical study of shocks overtaking multiple clumps was completed attempting to articulate the basic physical processes involved as well as differentiating clump parameter regimes. In that paper two regimes were described in which the neighboring clumps either did, or did not, interact as they were overtaken and destroyed by the flow. In addition, it was demonstrated that mixing of clump and ambient materials was affected by the distribution of clumps.

In spite of the computational advances which made the PFB study possible an understanding of the full 3-D dynamics of clumpy flows including the effect of microphysical processes is still not available. The problem is sufficiently complex that numerical methods can not be expected to fully articulate answers

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to the problem. Thus, additional investigative methods are warranted. In this paper we describe the design of a High Energy Density (HED) laboratory experiment to study shock propagation in clumpy flows. The advent of HED laboratory methods is a new development in the study of astrophysical phenomena (Remington *et al.* 1999, 2000) and may offer the opportunity to probe dynamical processes with control parameters that are not possible in traditional, observational approaches.

As with the numerical investigations of clumpy flows, the literature currently contains only experiments examining the interaction of a shock with a single clump. In (Klein *et al.* 2000) the NOVA laser was used to drive a strong shock ( $M \approx 10$ ) into a low-density plastic target with a single embedded copper microsphere. The morphology and evolution of the shocked “cloud” as well as the trajectory of the shock were tracked via radiography. The experiment was able to follow the shock-cloud interaction for a number of dynamical or “cloud crushing” times. These results were compared with 2.5 and 3-D simulations. The 3-D results used AMR methods that allowed significant details in the evolution of the shocked cloud to be determined. Klein *et al.* (2000) observed a flattening of the shocked cloud as well as the appearance of hollow interior. The hollowing was attributed to a breakup of the vortex ring that forms as the shock traverses the cloud. Robey *et al.* (2002) have reported further studies of this vortex ring breakup. Kang *et al.* (2001a) also carried out laboratory experiments of a shock interacting with a dense sphere embedded in foam. In these experiments a so-called “complex shock” (forward, reverse shock waves, and the intermediate contact discontinuity) was formed when a supersonic flow impacted low-density matter. The flattening of the cloud was again observed, as was the vortex ring on the downstream side of the cloud. Using 1 and 2.5-D simulations Kang *et al.* (2001b) tracked the evolution of the complex shock as well as the disruption of the cloud.

In the present paper we describe a design for an experiment that involves multiple dense clumps interacting with a strong shock wave. By its nature the clump problem is complex and care must be taken to create experiments that focus on specific questions lest one ends up with results too complex to analyze. Issues such as the role of interactions among clumps, the effects of multiple clumps on mixing and turbulence, and the nature of mass loading due to clumps could all be investigated with the correct design but it is unlikely that they can all be investigated with a single experiment. Thus, in this paper, we consider a design which is meant to study the global question of how a clumpy medium affects the dynamics of shock propagation. Specifically we focus on how a highly clumped medium alters the global shock propagation speed. This question is relevant to astrophysical flows, such as shocks traversing giant molecular clouds in which many cloud cores may exist or the progress of a supernova blast wave through a clumped wind ejected from the star during a previous epoch.

In section 2 we describe the experimental set-up. In section 3 we present simulations of the experimental set-up comparing targets with and without clumps, as well as the targets that have a smooth distribution of mass whose average density is equal to that in the clumped target. These results are of interest in their own right independent of this particular experiment. We note, in particular, that clumps and foams may be similar enough in principle for our simulations to bear on general issues related to inertial confinement fusion (ICF) and laboratory astrophysics experiments. In the final section we summarize and discuss our

results giving prescriptions for the set-up of these experiments on either intense laser or pulsed-power experimental testbeds.

## 2. EXPERIMENTAL DESIGN

Several goals for an experiment that is to explore the propagation of shocks through clumpy media can be identified. 1) The fraction of the volume occupied by the clumps should be realistic; we chose 5%. 2) The ratio of density in the clumps to density in the interclump medium should be realistic. Our choice was 40 to 1. This is on the low end of observed values; we chose it to maximize the heating of the clumps and for other reasons discussed below. 3) The shock wave in the clump region should be reasonably steady and enduring. Specifically, it should be sustained long enough so that it interacts with many clumps without any substantial change in the properties of the shock or the post-shock flow. 4) The experiment should allow comparison of the clumpy case with alternative cases, in which the shock wave propagates through media having either a density equal to the average density of the clumpy medium or a density equal to the interclump density. 5) The shock wave should be as strong as possible, in order to maximize the heating of the clumps. Ideally, the clumps should be ionized so that they can be accurately treated by an ideal-gas equation-of-state with a polytropic index  $\gamma = 5/3$ . 6) The experiment should be diagnosable using available techniques.

In seeking to meet these goals, we have developed the experimental design shown in Figure 1. The energy source for these experiments is a pulse power device known as a Z pinch, specifically the “Z Machine” operated by Sandia National Laboratories (Matzen 1997). A Z pinch can implode an array of W wires at high velocity, so that an intense x-ray pulse is produced when the wires collide and their kinetic energy is thermalized. Among existing high-energy-density research facilities, Z can deliver the most energy to a target. This is essential for an experiment that requires a (comparatively) large volume; the present experiment involving many clumps is a good example. Through the use of a surrounding, high-Z container (a hohlraum) to help contain the x-rays, it is feasible to irradiate up to 4 targets per implosion with an x-ray pulse whose spectrum is reasonably approximated as a blackbody spectrum with a temperature of 140 eV. The full-width half-maximum (FWHM) of this x-ray pulse is 8 ns.

The radiation-hydrodynamic computer code HYADES (Larsen & Lane 1994) was used to evaluate our design options. HYADES is a single-fluid, Lagrangian code in which the material composition can be different from cell to cell and in which the electron and ion temperatures evolve independently. The electron heat transport is by flux-limited diffusion, but this was not important here. The version of the code used here employs a single-temperature (“greybody”) radiation field with flux-limited, diffusive radiation transport. This was only important in the initial delivery of energy to the target. The code was run with SESAME equation-of-state tables. For our purposes here, what mattered in the radiation hydrodynamics was to deliver the correct amount of energy to the initial layer in the target. Accordingly, we adjusted the radiation temperature to obtain the correct ablation pressure for the measured radiation temperature, based on well-confirmed scaling relations (Lindl 1998). We also compared the behavior of targets simulated using a measured radiation pulse, which includes an extended, low-temperature foot at the start of the pulse, with the behavior using an approximate pulse of constant temperature and 8 ns

duration. These were very similar (the energy coupling is dominant). Therefore, a simpler 8 ns pulse was used for our scaling studies that developed the specific target properties.

The available x-ray pulse cannot be used to directly drive the desired shock wave. It is too brief, and one needs to absorb it by solid-density matter before driving the shock through a lower density material. The initial challenge in the design is thus to transform the x-ray energy into hydrodynamic energy, which eventually will be used to drive the desired steady shock. The most efficient way to extract energy from a radiation source is to allow it to accelerate a thin layer of material over some distance, while ablating some fraction of the initial layer (Ripin *et al.* 1980). The initial layer must be massive enough to provide the necessary momentum to the additional mass encountered later during the experiment. It also must be thick enough that instabilities at the ablation surface do not disrupt it. Scaling studies showed that a 125  $\mu\text{m}$  thick layer of polystyrene, at a density of 1 g/cc, worked well for this purpose. The range of optimum thickness is not narrow; one would obtain comparable results from thinner or thicker layers. The initial layer is accelerated across a 500  $\mu\text{m}$  vacuum gap. The size of the gap was optimized so that the plastic layer collides with the next layer in the target (the C foam) just at the end of the 8 ns drive pulse. At this time, it has been accelerated to a velocity of about 70 km/s.

The second design challenge is to convert the energy initially delivered by the 8 ns x-ray pulse into a form that can drive a shock for tens of ns, which turns out to be necessary for reasons discussed below. To accomplish this, we let the accelerated plastic layer impact a C foam layer of density 200 mg/cc and thickness 1.5 mm. Our goal here is to let a blast wave develop in the C foam, in which an abrupt shock is followed by a gradual deceleration over a significant distance. The areal mass density of the C foam is several times that of the plastic that remains when the foam is impacted, so that this blast-wave becomes approximately a (planar) Sedov-Taylor wave, decelerating slowly, accumulating mass, and growing spatially. Our goal is to use the rarefaction of the leading edge of this blast wave into the clumpy medium, to drive the enduring shock that we intend to produce. Here again, we used scaling studies to set the foam density and thickness. The C foam must be dense enough that its leading edge can drive the shock we require through the clumpy medium, yet not so dense that the shocked foam becomes too cool and the rarefaction becomes too slow. The changes in behavior were seen to be gradual, so that the specific parameters of the target represent specific conditions within a broad range of reasonable choices.

Figure 2 shows the evolution of the blast wave as it reaches the end of the C foam. By these times the initial plastic layer, seen as the dense feature on the left, has decelerated nearly to rest. The local modulations in density and velocity are acoustic and are artifacts of the zoning used in the simulation. The first profile shows the blast wave near the end of the C foam. One sees the characteristic abrupt shock and gradual deceleration. One can also see that the structure of the blast wave extends over several hundreds of  $\mu\text{m}$ . This enables it to deliver its energy for several tens of ns, with characteristic velocities of tens of km/s. When the blast wave reaches the interclump medium (solid profile), its velocity is  $\sim 33 \text{ km s}^{-1}$ . At that time, as seen in the other profiles, a rarefaction wave forms. This drives

a faster, reasonably steady shock into the interclump medium, as is expected for a centered rarefaction (Zeldovich & Raizer 1966)<sup>7</sup>. The rarefaction propagates backward into the C foam as well. However, no subsequent reflected shock is produced during the experiment because there are no density structures in the blast wave.

The properties of the clumpy medium were chosen based on several considerations. The interclump medium must be low in density to allow the rarefaction of the blast wave to expand at a high velocity and to allow diagnostic x-rays to penetrate distances of several mm for radiography. Subject to these constraints, higher values of this density produce larger ram pressures and more heating of the clumps. We chose 25 mg/cc divinyl benzene (DVB) foam for this material. This produced the minimum realistic ratio of 40 to 1 between the interclump medium and the plastic clumps at 1 g/cc. The value of 1 g/cc was the lowest density for clumps that could be implemented, leading to the maximum clump heating. The clumps were chosen to be two-dimensional rods since, on one hand, this was easier to diagnose and simpler to model and, on the other, since an approach to the manufacturing method of such a system could be identified. The choice of a 5% volume fraction for the clumps implied a relation between the radius of the clumps and the clump density. The choice of a clump size was subject to the competition between the goals of being able to make them and to diagnose them, which favored large clumps, and the goals of maximizing their temperature and of having many clumps in the experiment, which favored small clumps. The size of the clumps was chosen to be 50  $\mu\text{m}$ , corresponding to an average interclump spacing of 200  $\mu\text{m}$ , a clump density of 25 per square mm, with a total of 200 clumps in a 4 mm wide, 2 mm thick clumpy layer. The location of the clumps in the clumpy medium was chosen to be random, as is the case in actual clouds. This was accomplished by using an algorithm that employed a random number generator to specify these locations.

By using a DVB foam with a density of 73 mg/cc in place of the clumpy medium, one could observe the propagation of the shock wave through a medium of uniform density (at least on scales larger than the  $\mu\text{m}$ -cell size within the foam material). By using 25 mg/cc DVB foam without clumps, one could observe the propagation through the uniform interclump medium.

Beyond the clumpy medium, additional components are placed that allow the emergence of the shock to be detected and ideally also the subsequent velocity of the interface at the end of the clumpy medium to be measured. One approach is to place a quartz window, coated with a thin ( $\sim 1 \mu\text{m}$ ) Al layer, at the end of the foam and to diagnose the motion of the Aluminum layer interferometrically.

### 3. THEORETICAL AND NUMERICAL ANALYSIS

#### 3.1. Theoretical Background

The interaction of a shock wave with a clumpy medium has recently been analyzed by PFB in systems with different numbers of clumps and different clump arrangements. They were simulated numerically using an AMR code. Here we will give a brief summary of the results and will refer the reader to that paper for further details.

Analytical arguments drawn from examination of the simulations allowed two regimes of clumpy flows with distinct

<sup>7</sup> The density spike at the leading edge of the rarefaction, which is not important for the overall hydrodynamic evolution, is an artifact of the equation-of-state tables. It would not actually be present for the ionized material present here.

flow behavior to be identified. In the “interacting” regime, the evolution of individual clouds was strongly affected by their neighbors. As is well known (KMC), the behavior of individual shocked clumps in the adiabatic regime is dominated by compression and subsequent expansion in a direction perpendicular to shock propagation (flattening). When this expansion causes neighboring clumps to interact on a timescale shorter than the time for them to be destroyed by the post-shock flow, the subsequent evolution is more appropriately described as a larger merged system that then progresses toward turbulence. In the non-interacting regime the clumps are so widely separated that one can describe their evolution up to destruction in terms of a single shock-clump interaction. PFB found that clump distributions in the interacting regime showed more robust mixing between shock and clump material apparently due to stronger turbulent motions downstream. The enhanced mixing seen in PFB may have important consequences in astrophysical systems such as SNe and evolved stellar wind-blown bubbles where processed elements in the clumps will be dispersed through the ISM. In the noninteracting regime clumps will evolve independently until they are destroyed by the shock and the post-shock flow.

The concept of interacting and non-interacting regimes can be made more quantitative. For an external shock velocity  $v_s$ , a clump radius  $a_0$ , and clump to ambient density ratio  $\chi = \rho_c/\rho_a$  the key timescales are the shock crossing timescale  $t_{SC}$ , clump crushing timescale  $t_{CC}$ , and clump destruction timescale  $t_{CD}$ ,

$$t_{SC} \equiv \frac{2a_0}{v_s}, \quad (1)$$

$$t_{CC} = \left( \frac{\chi}{F_{c1}F_{st}} \right)^{1/2} t_{SC}, \quad (2)$$

$$t_{CD} = \alpha t_{SC}, \quad (3)$$

where  $F_{c1} \approx 1.3$  and  $F_{st} \approx 2.06$  for our experimental conditions. The first quantity relates the stagnation pressure with the pressure behind the internal forward shock in the clump, while the second relates the external postshock pressure far upstream with the stagnation pressure at the cloud stagnation point. The parameter  $\alpha$  is determined from the simulations and is typically 2. Therefore, systems with a clump density ratio of  $\chi = 40$  and a strong external shock (Mach number in the range  $M_s = 5 - 100$ ) yield  $t_{CC} \approx 3.9t_{SC}$  and  $t_{CD} \approx 7.8t_{SC}$ .

A critical separation,  $d_{crit}$ , perpendicular to the direction of shock propagation can then be derived and expressed as

$$\begin{aligned} d_{crit} &= 2(a_0 + v_{exp}(t_{CD} - t_{CC})) \\ &= 2a_0 \left\{ \frac{t_{CD} - t_{CC}}{t_{SC}} \left( \frac{F_{c1}F_{st}}{\chi} \right)^{1/2} \left( \frac{3\gamma(\gamma-1)}{\gamma+1} \right)^{1/2} + 1 \right\}, \end{aligned} \quad (4)$$

where  $\gamma$  is the adiabatic index of the constituent gas and  $v_{exp}$  is the lateral expansion velocity of the clump equal to the clump internal sound speed. When clumps are initially separated by a distance  $d > d_{crit}$  they will be destroyed before they interact. A similar quantity  $L_{CD}$ , the cloud destruction length, can be defined for the direction parallel to the direction of shock propagation. Expressions for  $L_{CD}$  are somewhat cumbersome, relying on a description of the acceleration of the clumps after the passage of the shock. Readers may find the relevant expressions in PFB.

To summarize, inhomogeneous flows will be in the interacting regime when initial clump distributions have average separations between clumps normal to the flow  $d$  such that  $d < d_{crit}$

and along the flow  $L < L_{CD}$ . In what follows we use these results in describing simulations exploring the experimental design described in the previous section.

### 3.2. Numerical Setup and Method

A series of numerical simulations based on the experimental design presented in Section 2 were performed. The simulations used the Adaptive Mesh Refinement (AMR) hydrodynamics code AMRCLAW (Berger & LeVeque 1998). AMR methods allow high resolution to be applied dynamically where needed in a calculation. Such methods are critical in studies of high Mach number clumpy flows as it would be impossible to properly resolve both the details of individual shock-clump interactions and the global flow with fixed grid methods. Description of the code and its application to the clumpy flow problem can be found in PFB.

Our clumpy flow simulations were performed in 2-D Cartesian geometry and are therefore slab symmetric. The simulations were initialized with a blast wave of properties described in Section 2 and corresponding to the solid profile in Figure 2, propagating into an array of 200 clumps distributed randomly. The properties of the clumps and surrounding media were also the same as described in Section 2. The particular distribution of clumps (each with  $a_0 = 25 \mu\text{m}$  and  $t_{SC} = 0.96 \text{ ns}$ ) used in the simulations had the following properties:

$$\begin{aligned} d_{crit} &= 4.26 a_0 = 106.5 \mu\text{m}, \\ L_{CD} &= 3.54 a_0 = 88.5 \mu\text{m}. \end{aligned} \quad (5)$$

Average clump separations in the experiment, calculated according to the expressions (39) and (40) of PFB, are

$$\begin{aligned} \langle \Delta x \rangle &= 5.35 \mu\text{m} \approx 6.05\% L_{CD}, \\ \langle \Delta y \rangle &= 10.24 \mu\text{m} \approx 15.88\% d_{crit}. \end{aligned} \quad (6)$$

Thus, the system designed for the experiments can be described as strongly interacting with both global and local evolution strongly affected by clump merging prior to breakup.

The details of our simulations were as follows. We used a 3 level system of refinement corresponding to a maximum equivalent resolution of  $3264 \times 2560$  zones. Thus, at maximum resolution each clump radius  $a_0$  was resolved with at least 16 zones. That resolution is significantly smaller than the resolution that would correspond to the converged regime (e.g., see (Klein *et al.* 1994; Poludnenko *et al.* 2002)). However, on one hand, such converged resolution was unfeasible with given computational resources. On the other hand, achieved resolution was sufficient to capture global properties of shock propagation in the clumpy medium which was the primary focus of investigation. The computational domain had dimensions  $160a_0 \times 204a_0$ . The shock entered the domain from the left. All four boundaries of the domain had outflow boundary conditions. In general, however, high density material, corresponding to the target walls and included in the computational domain, kept the flow from reaching the side boundaries for a rather large part of the simulation. Similarly, while the far side of the computational domain was an open boundary, the high density backplate kept the flow from exiting the grid during the simulation.

Three simulations were run corresponding to the likely program of experimental shots. Run 1 contained no clumps, Run 2 contained the clump distribution described above, and Run 3 contained no clumps but had a smooth background whose density was equal to the average density in the clump region of the clump run. All three runs lasted well past the moment of contact of the global shock with the backplate, namely the Run 1

was run for  $t = 76$  ns or  $\approx 79t_{SC}$ , Run 2 was run for  $t = 138.2$  ns or  $\approx 144t_{SC}$ , and Run 3 was run for  $t = 70$  ns or  $\approx 73t_{SC}$ <sup>8</sup>.

### 3.3. Results

Figure 3 shows a snapshot of the clumpy simulation early in its evolution after 15.89 ns ( $16.55 t_{SC}$ ) and is a synthetic Schlieren representation of the logarithmic density in the flow. A number of points are worth noting. By this time the first “row” of clumps has already been destroyed and the material from these clumps has been accelerated downstream. The effect of this first line of clumps on the downstream neighbors can be clearly seen in this figure. The second “row” of clumps is disrupted both by the passing of the global shock as well as by the debris from the upstream clumps. Thus, the kinetic energy in the flow  $F_k$  interacting with these clumps is enhanced above that for single clumps as

$$F_k = \frac{1}{2} \rho_{PS} v_{PS}^2 + F_C = \frac{2\rho_0 v_S^2}{(\gamma-1)(\gamma+1)} + \frac{1}{2} \langle \rho_{CA} \rangle v_C^2. \quad (7)$$

Here  $\rho_{PS}$  and  $v_{PS}$  are the post-shock density and velocity respectively,  $\rho_0$  is the unshocked interclump density, and  $v_S$  is the global shock velocity. The first term corresponds to the undisturbed post-shock flow. The second term encompasses the accelerated clump material and it depends on its instantaneous velocity  $v_C$  (expressions for it can be found in PFB) as well as the details of its dispersion, i.e.  $\langle \rho_{CA} \rangle$ . As was shown in PFB, such interactions greatly enhance mixing, and more importantly for our purposes, rob the shock of energy by converting bulk flow into a turbulent cascade of vorticity.

In Figure 3 notice also the presence of the individual bow shocks surrounding each clump. As the incident shock progresses, these individual shocks merge into a single structure. This merged structure becomes normal to the direction of the flow eventually taking the form of a single reverse shock. Thus, we see a clear transition from a flow pattern in which the heterogeneity dominates initially to one in which a global flow dynamics emerges. It is worthwhile noting that considerable acoustic structure can be seen behind (to the left) of the global reverse shock as information about newly shocked clumps propagates upstream.

Finally, notice that while the global shock has numerous corrugations in it due to the presence of the clumps we do not see any large scale disturbances. This trend continues for the entire evolution of the simulation. On average, the shock appears to “anneal” itself as it passes through the clump region. The global structure of the shock upon passing through the clumpy region and the effect of “annealing” can be studied in the experiment via the diagnostics of the interaction of the shock with the Al layer on the backplate.

The global behavior of the incident shock is illustrated in Figure 4 that shows the progress of the shock as a function of time for all three simulations. For the clumpy simulation this figure was made by constructing an average position for the shock from different samplings along strips in y-direction. The process was performed by locating the global shock position. An estimated error is of about the cell size at the level with the highest resolution, which is about  $1.6 \mu\text{m}$ . This figure demonstrates how shock propagation will differ in a clumpy flow from that in a smooth one, even when the smooth flow has the same average properties. Initially, shock front velocity in the clumpy case is virtually identical to that when the clumps are absent.

However, as the shock propagates further through the clumpy region, causing more clumps to be destroyed, its velocity gradually starts to decrease. As the whole clumpy system breaks up and homogenizes, the global shock velocity would eventually tend toward the values that correspond to the case of a uniform averaged density medium. The time for the clumpy system to change its behaviour from the one similar to the case with no clumps to the one similar to the case with average density is on the order of the system destruction time  $t_{SD}$ . Definition of  $t_{SD}$  is given in section 3.1.2 of PFB. It should be noted, however, that from the experimental point of view it was unfeasible to provide extended region behind the clump section of the target to follow clump system evolution after its break-up for some period of time. Since in our simulations we tried to reproduce the target design as closely as possible, we were not able to observe the shock front velocity evolution beyond the point of its emergence from the clump system and contact with the backplate.

Average values for the shock velocities derived from Figure 4 are:  $\langle v_{s1} \rangle \sim 57.1 \text{ km s}^{-1}$ ;  $\langle v_{s2} \rangle \sim 51.95 \text{ km s}^{-1}$ ;  $\langle v_{s3} \rangle \sim 44.94 \text{ km s}^{-1}$ . Thus the shock in the clumpy case propagates 15.6% faster than in the situation with the same average density but no inhomogeneities. This is an important point that may have significant consequences for astrophysical flows as we discuss in the final section. From the design standpoint, however, note that the time resolution associated with the diagnostic modes of shock detection to be used in the experiment is about 100 ps, whereas the difference between the shock arrival time at the backplate for those two cases is about 6 ns. Thus, data taken from the shots should be capable of distinguishing between the various cases - an important point for the development of a successful test bed for studying clumpy flows.

Figures 5 and 6 show synthetic X-ray backlighter images of the clumpy simulation at 15.89 ns. Figure 5 is an image using 5 keV X-rays with a maximum optical density on the film of 2.0, and Figure 6 is an image using 10 keV X-rays with the same maximum film density. The images were calculated using cold material x-ray attenuation coefficients and a linear  $\log(\text{exposure})$  to optical density relation.

The 5 keV X-ray radiograph of Figure 5 shows the structure of the global shock wave as it propagates through the medium in which the clumps are embedded. The shock front and subsequent shock waves from the clumps are clearly visible. The effect of the shock wave on the clumps is shown by the higher energy X-ray radiograph of Figure 6. The collapse of individual clumps as the shock wave interacts with them is apparent.

## 4. DISCUSSION AND CONCLUSIONS

In this paper we have presented a design for an experiment to explore the evolution of a strong blast wave propagating through a clumpy medium. These experiments are relevant to astrophysical shocks propagating through a variety of inhomogeneous environments including young stellar objects, supernova remnants, planetary nebulae, and AGN. Our experiment begins with a shock wave created by the acceleration of a slab of material via energy deposition from a pulsed power source. The blast wave propagates first through a smooth region of low density foam followed by a region in which plastic rods are embedded in a foam background. We have described the nature of the blast wave and the properties of the foams that constitute the “ambient medium”, as well as the rods that constitute the clumps. We note that, while these experiments are described in

<sup>8</sup> Hereafter in our simulations time is given from the moment when the blast wave enters the low-density interclump medium.

the context of the Z-pinch pulsed power machine, our design could be adopted to other high energy density devices such as high intensity lasers (Boehly *et al.* 1995; Paisner *et al.* 1999).

Numerical simulations based on the experimental design confirm that the experiments should be capable of exploring differences between shocks propagating through: 1) smooth media; 2) clumpy media; 3) smooth media whose properties correspond to the average properties of clumpy regions. Our simulations show that shocks in clumpy media move more rapidly than those in the smooth media with averaged properties. The shock speed in the former case is  $7.01 \text{ km s}^{-1}$ , or 15.6%, higher than in the latter for the experimental conditions. This difference is sufficiently large to be resolved by existing diagnostics. Thus, the experiments should be able to explore issues surrounding energy deposition in the evolution of clumpy flows.

Our simulations have already revealed behavior that may bear on the evolution of clumpy astrophysical flows. Our results indicate that the use of average properties of inhomogeneous regions in calculations of critical timescales may be inappropriate and lead to incorrect conclusions. Consider, for example, the propagation of a strong shock impinging on a molecular cloud of size  $L$  which contains many dense cores. Considering that the shock compression of the cores may trigger gravitational collapse, one would be interested in comparing the cloud crossing timescale for the shock to propagate across the cloud to the time associated with the collapse of an individual core. Determination of the relative size of these two timescales would establish the environments in which star formation would occur. For example, when  $t_{\text{cross}} \ll t_{\text{col}}$  then one can ignore any ongoing interaction between the shock and the collapsing core. Our results, however, indicate that care is needed in determination of  $t_{\text{cross}}$  since  $t_{\text{cross}} = L/v_S$  where  $v_S$  is the shock speed in the cloud. Since  $v_S$  is a function of conditions in the cloud such as the density  $\rho_c$ , our results indicate that replacing the spatially inhomogeneous  $\rho_c(x, y, z)$  (appropriate to a clumpy medium) with the average  $\langle \rho_c \rangle$  can lead to an overestimation of the  $t_{\text{cross}}$ . While these issues require more study, the simulations presented in this paper (along with those presented in PFB) indicate that global dynamics of clumpy flows may not be easily captured by simple smoothing through the use of spatial averages.

These results may also have implications for the behavior of foam targets themselves. Some foams are composed of many small bubbles, so that a shock wave will propagate through a random sequence of bubble walls, causing them to expand and creating many small local shocks and rarefactions. Other foams have the morphology of a pile of straw with long rods separated by spaces. This case has more resemblance to that studied here, as the shock will propagate around the rods, which will subsequently be destroyed. However, the vacuum between the rods implies that in this case also local rarefactions will play an important role (unless preheat has caused the release of gas throughout the foam). In both these cases, the actual equation of state of the foam is complex and depends on the history of the material, at least when preheat and shocks are present. In addition, the post-shock state of the foam is likely to include turbulent motions that take up a non-negligible energy fraction, which implies that the EOS of the shocked foam may differ from that of an ordinary plasma for some period of time. Studies similar to those reported here, but in better optimized morphologies, could contribute to better understanding of the detailed behavior of these systems.

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The most recent results and animations of the numerical experiments, described above, as well as the ones not mentioned in the current paper, can be found at [www.pas.rochester.edu/~wma](http://www.pas.rochester.edu/~wma).

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FIG. 1.— The target and its components, described in the text. **Please, see additional file figure1.eps for the figure.**

FIG. 2.— Evolution of the density and velocity as the blast wave enters the low-density interclump medium. The profiles are labeled with the time in ns. **Please, see additional file figure2.eps for the figure.**

FIG. 3.— Synthetic Schlieren image of the density logarithm from the simulation of the experimental design with clump region. The shock propagates toward the right into the region of plastic rods. Image taken 15.89 ns after the blast wave entered the low-density interclump foam. Note the bow-shocks forming around the individual clumps and the destruction of the first row of rods. Position values correspond to the ones in Figures 1 and 2. **Please, see additional file figure3.eps for the figure.**

FIG. 4.— Plot of shock position vs. time for three simulations: 1) Run 1: no clumps, background density only; 2) Run 2: clumps; 3) Run 3: no clumps but with background density equal to the average density in the target with clumps. The two horizontal lines indicate the extent of the clumpy region in the simulations and the target. **Please, see additional file figure4.eps for the figure.**

FIG. 5.— Synthetic X-ray back lighter image of the clumpy simulation at 15.89 ns for the 5 keV X-rays. **Please, see additional file figure5.eps for the figure.**

FIG. 6.— Synthetic X-ray back lighter image of the clumpy simulation at 15.89 ns for the 10 keV X-rays. **Please, see additional file figure6.eps for the figure.**

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